STUDIES OF THE CYCLE OF GLACIATION

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I. THE CYCLE OF MOUNTAIN GLACIATION WITHIN MODERATE LATITUDES

In a general discussion of glacial sculpture in mountains,[2] the writer has made use of the terms *grooved* or *channeled upland* and *fretted upland* to describe respectively the early and the late effects of the erosional action of mountain glaciers. The Bighorn Mountains in Wyoming and the Swiss Alps were chosen as type examples of these contrasted erosion surfaces, the characteristics of which are, that in the former large areas of the preglacial upland still remain (Figs. 1, 2, and 3), while in the latter its complete dissection by cirque recession and enlargement has resulted in a system of main and secondary rock palisades described as comb ridges. Between these contrasted land surfaces many gradations exist, though examples of the former are relatively uncommon. Similar to the channeled upland of the Bighorn Mountains, though with less of the preglacial surface retained, are portions of the Uinta and Wasatch mountains, of which excellent illustrations have been supplied by Atwood.[3] All the best examples are furnished by the Rocky Mountains in the interior of the American continent, where the moist westerly winds have been robbed of their moisture in crossing the high Sierra Nevada and Cascade ranges.

In a visit to the Glacier National Park, the writer was impressed with the fact that a type of topography is there represented which indicates a still later stage of sculpture by mountain glaciers than

[1] Illustrations from photographs by the author.

[2] "The Cycle of Mountain Glaciation," *Geogr. Jour.*, Vol. XXXV (1910), pp. 147–53, Figs. 1–19. Also, "Characteristics of Existing Glaciers," pp. 25–40, Pls. 3–9.

[3] "Glaciation of the Uinta and Wasatch Mountains," *U.S. Geol. Survey, Prof. Paper 61* (1909), maps of Pl. 8A.

does the fretted upland as exemplified by the Alps. The most striking peculiarities of this type are found in the unusual number of isolated sharp peaks of monumented aspect (Figs. 4 and 5), and this is combined with a general absence of the comb ridge (a rare example is shown in Fig. 6) and a frequency of unusually low cols or passes (Fig. 7). Unlike the true horns of the Matterhorn type, which in the fretted upland are relatively few in number and may perhaps represent by their summits points near the original surface of the upland, the monuments of the northern Rocky Mountains show a tendency to appear in pairs, and in many

FIG. 1.—View of Mt. Mathews, Bighorn Range, taken from the southeast and showing the character of the preglacial surface. At the left in middle distance is a cirque.

instances at least they are remnants of lower portions of the preglacial surface (Figs. 5, 8).

Both in the Bighorn Range and in the Glacier National Park the glaciers have today nearly or quite disappeared, being now represented by small horseshoe or cliff glacierets only. The earlier conditions of nourishment were, however, as we know from more or less extended studies, notably different from those of today. In the Bighorn Range the glaciers of Pleistocene time extended far down the valleys, where strong terminal moraines are found to mark the limits of their advance.[1]

[1] R. G. Salisbury, "Cloud Peak–Sheridan Folio," *U.S. Geol. Survey;* also, N. H. Darton, *U.S. Geol. Survey, Prof. Paper 51*, pp. 71–91, Pls. 37–36.

FIG. 2.—View of cirque above Seven Brothers Lakes, seen from the ridge south of Trail Lodge, Bighorn Range.

FIG. 3.—Nearer view of the cirque shown in Figure 2. Characteristic surface of preglacial area in foreground.

In the Glacier Park district the Pleistocene glaciers occupied the entire valleys within the range and spread out eastward their aprons of Piedmont type. They also extended westward a long distance down the valley of the Flathead River.[1]

It is here proposed to use the term *monumented* upland to describe the extreme type of mountain sculpture which is represented in the Glacier National Park and which is believed to be due to continued glacial action upon a fretted upland like that of the Alps. Cirque enlargement carried to this stage has sapped the

FIG. 4.—View of Reynolds Mountain, a characteristic monument of the Glacier National Park region. View taken from the trail to Piegan Pass.

main comb ridge so as to largely obliterate the *aiguille* type of crest or *arête* (Fig. 6 shows one of the remaining comb ridges). Matterhorns have in the process been reduced in size as the cols are progressively lowered and widened and are transformed into *arêtes*. The last remnants of the upland to be removed by this continued cirque enlargement are found away from the original divide and outward toward the flanks of the upland, for the reason that in their later stages cirques enlarge excessively on their lateral walls. A good illustration of this tendency is supplied by the

[1] Wm. C. Alden, "Pre-Wisconsin Glacial Drift in the Region of Glacier National Park," *Bull. Geol. Soc. Am.*, Vol. XXIII (1912), Pl. 37. See also by same author, "Glaciers of Glacier National Park," and especially the map opposite p. 32.

FIG. 5.—A pair of monuments of monumented upland seen from the Piegan Trail, Glacier National Park.

FIG. 6.—View of a comb ridge looking across the Piegan Pass, Glacier National Park.

gently sloping summit plane of Quadrant Mountain in the Yellowstone National Park at an elevation of between 9,000 and 10,000 feet[1] (Fig. 9), since Antler Peak and Bannock Peak guard the entrance to the cirque.

It is especially because the comb ridges in the highest levels are precipitous and correspondingly thin that a continuation of

FIG. 7.—Gunsight Pass, seen from Gunsight Chalets looking across Gunsight Lake, Glacier National Park.

the process removes their pinnacles while the broader ridges somewhat farther out and just below the mother-cirques are being sharpened into peaks, both alike through sapping from the cirques.

To bring together the extremes of mountain glacier erosion which are represented by the Bighorn Range and the Glacier National Park with the intermediate stages which connect them, the four generalized plans of Figure 10 have been prepared. In order, these are:

I. The youthful channeled or grooved upland
II. The adolescent early fretted upland
III. The fretted upland of full maturity
IV. The monumented upland of old age

[1] "The Cycle of Mountain Glaciation," *Geogr. Jour.*, Vol. XXXVI (1910), Figs. 8, 14.

These four stages are perhaps best illustrated by the Bighorn Range, the mass of Snowden in the Welsh highland, the Alps, and Glacier National Park (Fig. 10).

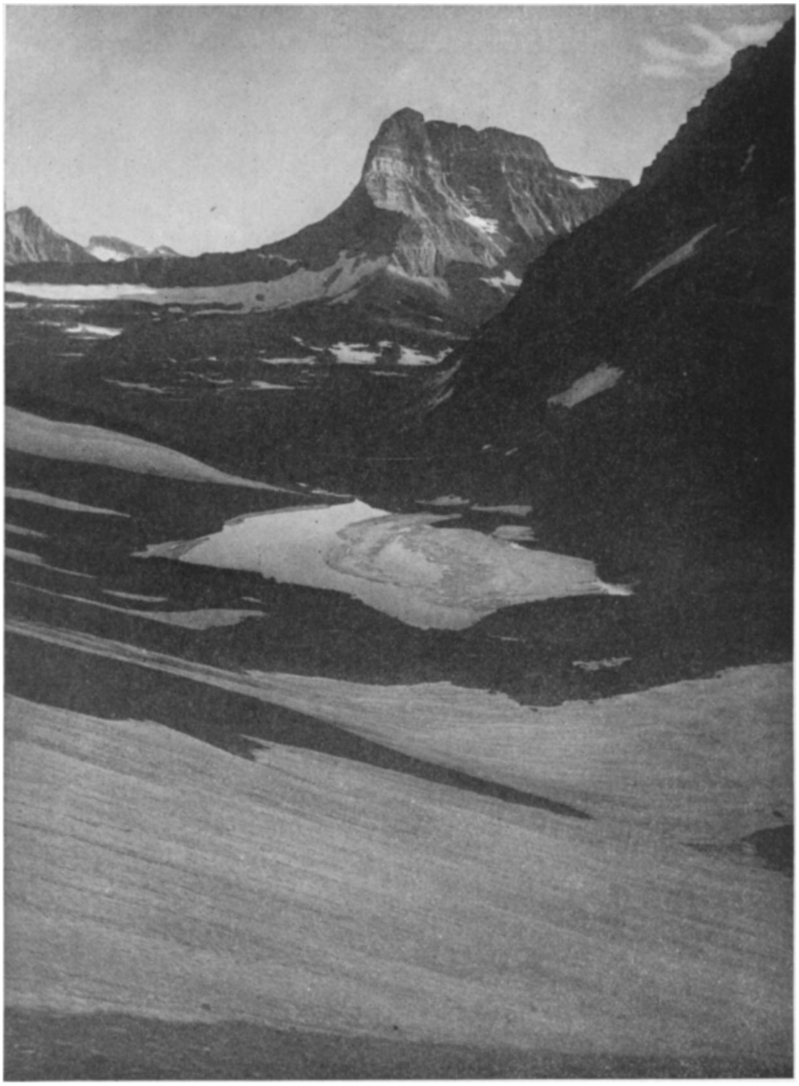


FIG. 8.—Monuments on either side of entrance to cirque above Ptarmigan Lake, Glacier National Park. (Photograph purchased of Northern Pacific Railway.)

The two districts which are here contrasted, the Bighorn Range and the Glacier National Park, furnish also the opportunity to contrast the effects of rock structure in modifying the forms of relief shaped by mountain glaciation. Whereas the high upland of the Bighorn Range has a core of massive rock, thus resembling the Wasatch and Uinta ranges and the Alps, the rocks of Glacier National Park are sediments and dominantly shales and limestones. It was to be expected that the characteristic structures of these

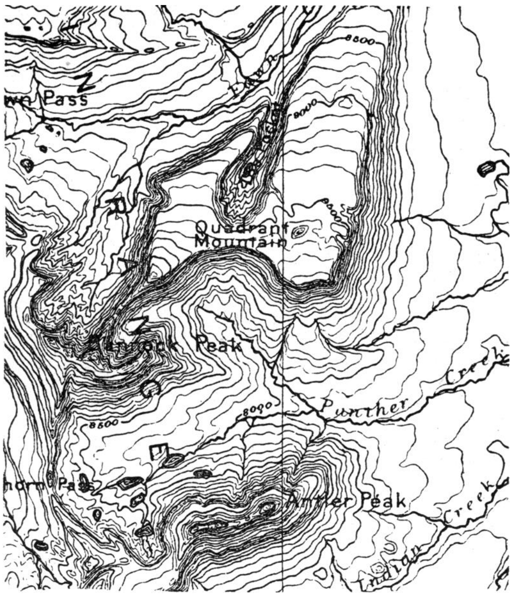


FIG. 9.—Cirque at head of Panther Creek, Yellowstone National Park, with pair of monumented peaks at entrance—Antler Peak and Bannock Peak.

sediments, their bedding planes and their joint system, should exert a strong influence upon the topographic forms produced, as indeed they have. The influence of the bedding planes is displayed in the Glacier National Park in the accentuation of the rock terraces at the upper ends of valleys within the cirques themselves. As in the Canadian Rockies across the international boundary, this character reaches an extreme (Fig. 11). An excellent instance is shown also in an illustration by Alden.[1]

[1] *Glaciers of Glacier National Park*, Fig. 11.

To the well-developed jointing found in the rocks of the Glacier National Park must be ascribed the well-marked checkerboard pattern displayed by the park valleys, a pattern which strikes one at once when the topographic map is examined. A number of observations of the bearings of master-joints which were made by

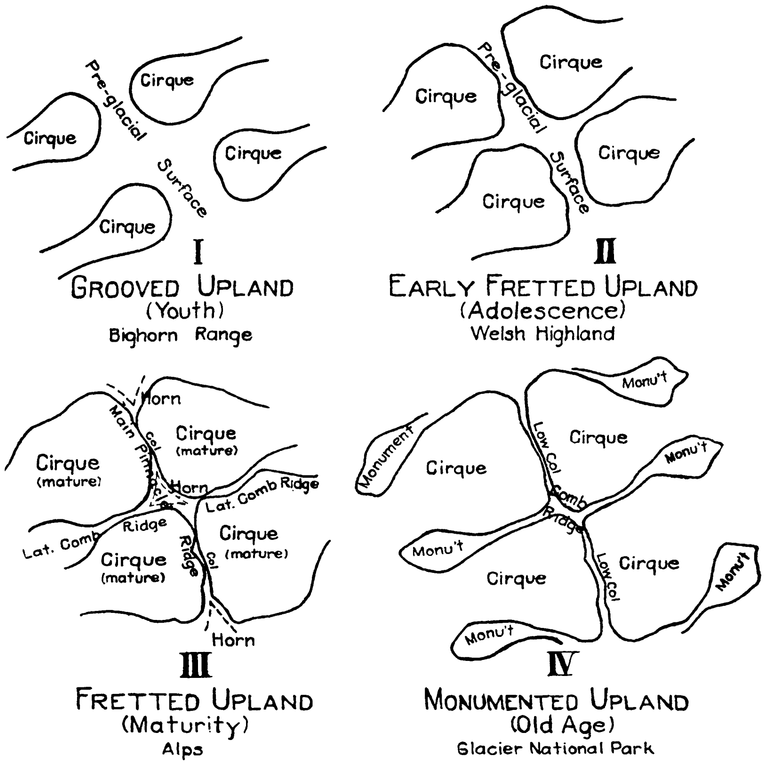


FIG. 10.—Stages of sculpture by mountain glaciers

the writer indicated a rather general correspondence between them and the trends of the valleys in which they were found. In some instances the lower spurs which have been less extensively sapped by glacial erosion indicate very clearly the dominating influence of the joint planes in shaping them. The cirques themselves also display this tendency by their approach to rectangular outlines.

II. THE TRANSITIONS BETWEEN THE MOUNTAIN GLACIER AND THE ICE CAP

From the standpoint of the sculpturing of the lithosphere, the ice cap is sharply set off from all types of mountain glacier through its inability to accomplish a sapping of rock surfaces due to rapid frost-weathering. Its sculpturing processes are therefore restricted to plucking, abrasion, and to a very limited extent frost-weathering on flattish surfaces—processes which in combination leave the rock rounded and presenting surfaces which are flatly convex

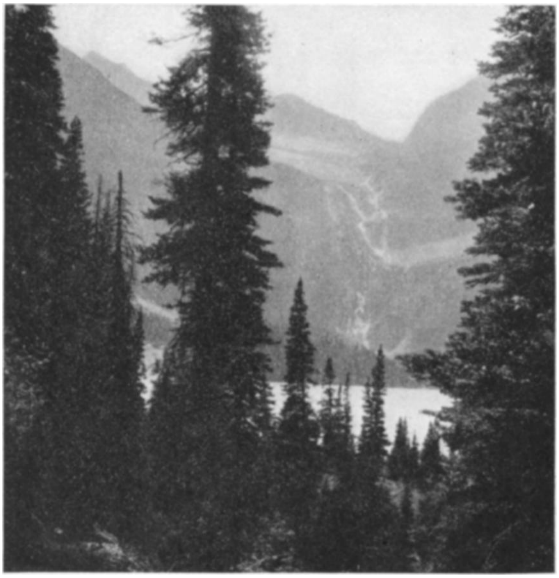


FIG. 11.—View of terraced cirque above Lake Grinnell, Glacier National Park

skyward. That these processes combined play but a subordinate rôle to frost-weathering in the case of all the types of mountain glaciers, would seem to be sufficiently attested by the sharply accented features which are brought about with their concavities toward the sky.[1]

Since the mountain glacier owes its very existence to a rock container within the lithosphere surface, the inclosing rock walls

[1] Hobbs, *Earth Features*, etc. (1911), p. 379, Fig. 405.

must in general project above the ice of the glacier. The rock surface will also be reached by air and water wherever crevasses descend through the ice of the glacier to the bed upon which it rests. The conditions essential to the sapping process are a supply of water on the rock surface and oscillations of temperature about the freezing-point. These conditions are not realized either in the case of ice caps or of continental glaciers, save only where nunataks emerge from beneath the ice near to the glacial margin.

When during an advancing hemicycle of glaciation a mountain glacier is so amply nourished that the rock walls of its containing basins become entirely submerged (ice-cap stage), a profound and immediate transformation takes place in the sculpturing processes.

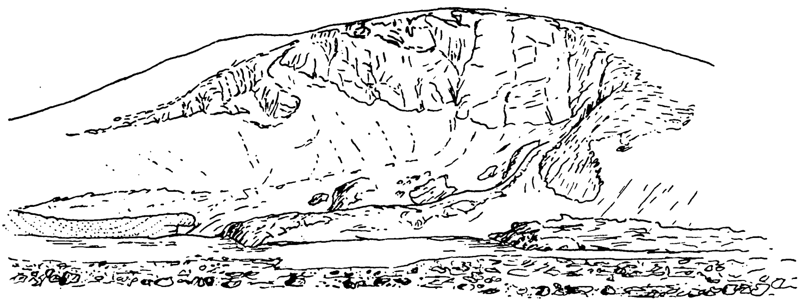


FIG. 12.—The northern cirque (Kjedel) on Galdhöpig in the glaciated surface of Norway. (After E. Richter.)

Up to this time, under the dominating influence of the sapping process, the effect of the glacial sculpture has been to sharpen all projecting features of the relief as the glacial basins and channels are carved deeper and extended outward from each individual locus. Now, however, under the plucking and grinding processes alone, which have usurped the functions of the frost-weathering, the pinnacles and horns within the comb ridges are truncated and ground down, with the result that above the shallowed cirques and the largely obliterated U-valleys there extends a flatly convex surface like that which is fashioned by the same processes beneath a continental glacier. The sharp relief which was inherited from the period of mountain glaciation is thus gradually ironed out into a flatly convex surface which is everywhere ground and polished by abrasion. The U-valleys are first effaced, beginning at their

lower extremities, and the last of the hollowed features of the inherited surface to disappear are the increasingly truncated remnants of the cirques, which in their later stages take the form of an armchair-like depression. Such features are well displayed in Norway where the continental glacier has similarly ironed out the inherited grooved or fretted upland (Fig. 12).

Such a surface as succeeds to a fretted upland under the sculpturing action of either an ice cap or a continental glacier will resemble in form a grooved glacial upland of extreme youth such as is illustrated by the Bighorn or Uinta ranges of the Rocky Mountain region, but it has less pronounced relief and, unlike such a preglacial remnant ("biscuit-cut" surface), *the upwardly convex surfaces are here planed and polished by abrasion.*

In the receding hemicycle of glaciation which succeeds to the culmination of glacial alimentation, the flat dome of the ice which constitutes the ice cap will have its surface progressively lowered until the stage is reached at which the rims of the buried cirque remnants begin to emerge from beneath their mantle of ice. In West Antarctica, near the winter quarters of the Swedish Antarctic Expedition of 1901–3, ice caps now blanket both James Ross and Snow Hill islands, and, like all Antarctic glaciers, they are in a receding hemicycle of glaciation. On the first-named island the rims of the cirques have emerged from beneath their cover along the eastern and southern margins of the island (Fig. 13). The Gourdon and Rabot glaciers are already apparently in large part detached from the dome of the ice cap, which here rises to its highest point in the Haddington berg. In the largest of the cirques lies the Hobbs Glacier, which is still in part fed by two ice cascades situated near the middle of the rim.[1]

Except that the continental glacier, and not an ice cap, has been the modeling agent, Mount Washington in the White Mountains[2]

[1] Otto Nordenskjöld, "Die schwedische Südpolar-Expedition und ihre geographische Tätigkeit," *Schwedische Südpolar-Expedition, 1901–3,* Vol. I, Lieferung 1 (1911), pp. 154–55, Map 3 and Pl. 13, Fig. 1.

[2] J. W. Goldthwait, "Following the Trail of the Ice Sheet and Valley Glacier on the Presidential Range," *Appalachia,* Vol. XIII (1912), pp. 1–23 (reprint), Pls. 1–9; "Glacial Cirques Near Mt. Washington," *Am. Jour. Sci.,* Vol. XXXV (1913), pp. 1–19; "Remnants of the Old Graded Upland on the Presidential Range of the White Mountains," *ibid.,* Vol. XXXVII (1914), pp. 451–53; "Glaciation in the White Mountains of New Hampshire," *Bull. Geol. Soc. Am.,* Vol. XXVII (1916), pp. 263–94, Pl. 13.

and Mount Ktaadn in Maine[1] would appear to supply near parallels to the sculpture just described, since the "gulfs" of the districts have been clearly recognized as cirques. Tarr has claimed that the mountain glaciers which sculptured the cirques on Mount Ktaadn

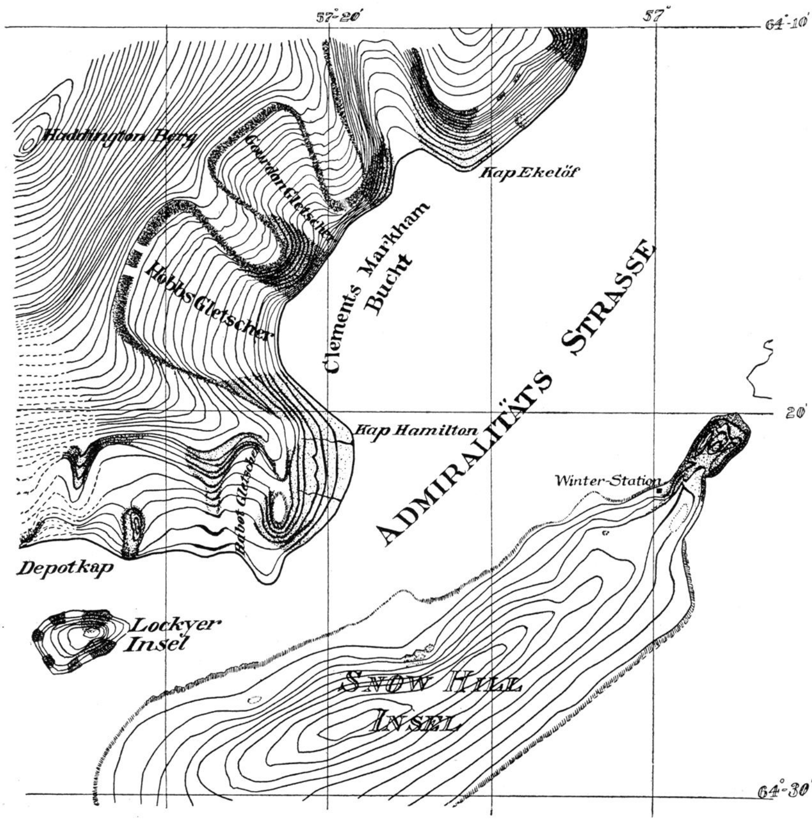


FIG. 13.—Map of portions of the James Ross and Snow Hill Islands of West Antarctica. (After Otto Nordenskjöld.)

were subsequent to the continental glaciation of the region. This is disputed by Goldthwait, who brings forward evidence to prove that in the White Mountains the mountain glaciers were antecedent to the continental glaciation which shaped the higher and flatter rock surfaces. We hardly see how there could fail to be glacial

[1] R. S. Tarr, "The Glaciation of Mt. Ktaadn," *Bull. Geol. Soc. Am.*, Vol. XI (1900), pp. 433–48.

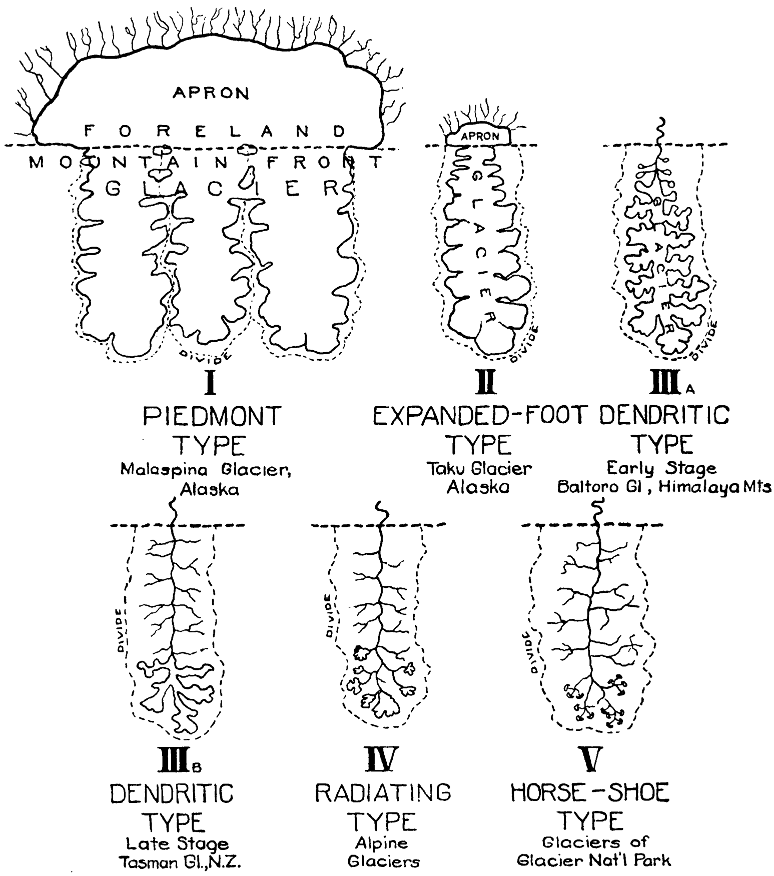
remnants in occupation of the cirques for at least a brief period while the continental glacier was withdrawing from the region. These would presumably develop in much the same manner as those already described on James Ross Island, but with differences which will be pointed out in the next section of this paper. Goldthwait is no doubt correct in believing that the mountain glaciers had a much longer life during the advancing hemicycle of glaciation and that the cirques were shaped at that time. It is even doubtful if any appreciable work of erosion or deposition was accomplished in the later period of mountain glaciation, and this interpretation would be in harmony with Goldthwait's observations.

III. THE GLACIAL CYCLE ON THE MARGINS OF THE CONTINENTAL GLACIER OF ANTARCTICA

It is a fundamental and prerequisite condition for the sequence of stages through which mountain glaciers pass during a receding hemicycle of glaciation that the areas of alimentation and ablation should be sharply separated from each other. The former is restricted to the upper levels, and alimentation is augmented in amount toward the top, whereas the area of wastage is found in the lower levels and the losses are increased toward the bottom. Such a distribution results principally from two conditions: (1) mountain glaciers are nourished by upwardly directed air currents which deposit their moisture as a result of progressive adiabatic refrigeration; and (2) they are wasted by contact with warm-air layers whose temperature rises progressively toward the bottom. *It is a direct consequence of the combination of these conditions that mountain glaciers during a receding hemicycle of glaciation become reduced in area through withdrawal of the glacier foot up the valley, and even in its expiring stage the glacier head occupies essentially the same position that it did at the beginning* (Fig. 14).

Were these two conditions affecting the size of mountain glaciers not realized, the results would be quite different. When we examine the glaciers on the margins of the inland ice of the Antarctic, we find they differ widely from those of moderate latitudes, which are the ones that are well known and have formed the basis of our classification. Within the Antarctic air temperatures do not rise

above the freezing-point even in the summer season, save only during short intervals at the termination of the fierce Antarctic blizzards. Furthermore, these marginal glaciers to the inland ice are nourished, not by inwardly and upwardly directed air currents,



GLACIER TYPES OF RECEDING HEMICYCLE
Progressive Withdrawal of Glacier Foot

FIG. 14

as are the mountain glaciers of moderate latitudes, but by downwardly and outwardly flowing currents which bring drift snow from the inland ice and often carry it beyond the marginal glaciers to be dissipated upon the surface of the sea. *Separate areas of*

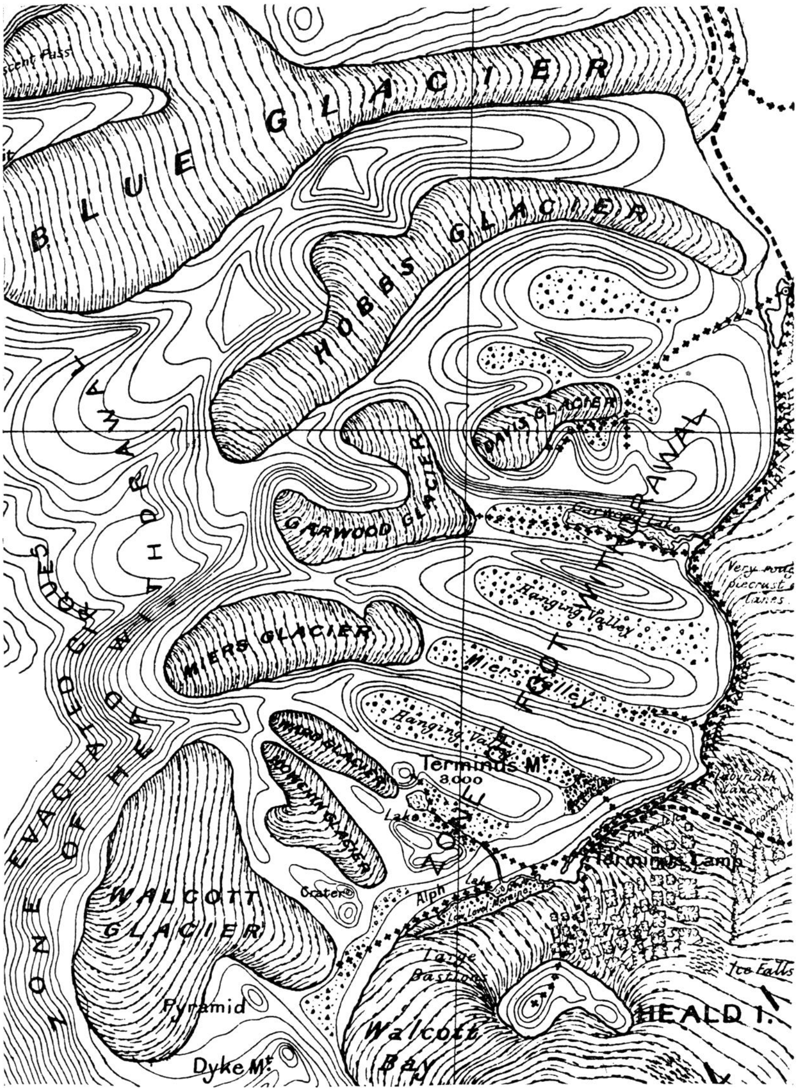


FIG. 15.—Map of an area in South Victoria Land near the winter quarters of the last Scott Expedition, showing waning glaciers which are withdrawing at both their upper and their lower margins. (After Griffith-Taylor and others.)

nourishment and waste in distribution with reference to altitude are thus not realized, and the otherwise universal law of exclusive drawing in of the foot of the glacier during its waning stages does not hold.

That this is true is particularly well shown in the area of waning glaciers described as "ice-slabs" by Ferrar, the glacialist of the first Scott Expedition to the Antarctic, and fully mapped by Griffith-Taylor, Debenham, and Wright of the last Scott Expedition[1] (Fig. 15). On a far larger scale and related to a continental glacier rather than an ice cap, these dying glaciers represent a later stage than those marginal types which have already been referred to from West Antarctica—the Gourdon, Hobbs, and Rabot glaciers of James Ross Island.

By examination of the map (Fig. 15) it will be noted that these glaciers must in an earlier stage have been connected together as a piedmont which was then a part of the parent area of inland ice lying to the westward. From that continental glacier when detachment occurred the rims of the battery of remodeled cirques which rise west of the existing glaciers must have emerged from the ice mantle in forms not unlike those now seen on the margins of James Ross Island. *Their subsequent diminution in size has gone on through withdrawal both from the cirques and from the lower portions of their valleys—from both extremities toward a central position at a moderate altitude, where the last stand will be made before final extinction.*

The usual law of ablation regulated with respect to altitude here plays, therefore, no part, and it is evident that the reflection and consequent intensification of solar heat radiation in the neighborhood of exposed rock walls has here been the controlling factor in localizing the wasting process. This effect of exposed rock surfaces has been recognized for high latitudes by the observation of moats surrounding nunataks[2] and of the lateral streams beside glacier tongues[3]

[1] Robert F. Scott, *Scott's Last Expedition*, Vol. II, map opposite p. 198.

[2] "Characteristics of Existing Glaciers," pp. 169, 257, Pl. 33B.

[3] *Ibid.*, Pl. 25A.